

## Preface

Reviews on the historical growth of the semiconductor industry usually refer to the prediction by Gordon Moore in 1975 that circuit density would double every couple of years. The realization of this dramatic increase in integration over the last twenty-five years has been achieved primarily through lithographic scaling, resulting from many innovations in lithographic exposure systems, masks, resists, processes, and metrology. Throughout this period IBM has made many of the most significant contributions to the development of semiconductor lithographic technology. These contributions were often made long before industry adoption and frequently involved innovations across multiple disciplines.

Some of the IBM results in process and resist materials from the 1960s and 1970s are so ingrained in the industry that they are taken for granted. Perhaps the best example of this is the initiation by IBM in the mid-1960s of the use of hexamethyldisilane (HMDS) as an adhesion-promoting agent (for improving the adhesion of resist to silicon oxide surfaces). Since then, the large majority of resist applications to wafers have been preceded by HMDS treatment of the surface. Another example is the work of IBM researchers in 1975 using post-exposure bake to eliminate standing-wave patterns formed by optical interference in resist. This procedure is now routinely used. Earlier (in 1970), IBM process engineers discovered that aqueous tetramethyl ammonium hydroxide (TMAH) could be employed as a resist developer. This has since become the developer of choice because it is water-based, gives excellent imaging, and is free of metals that could potentially poison silicon devices. Many other techniques common in modern microelectronics fabrication facilities originated in IBM. The use of deep-UV radiation to harden resist against thermal deformation during subsequent harsh processing is another case in point.

IBM pioneered the use of deep-UV lithography (248 nm) for semiconductor fabrication. In 1975, Lin proposed deep-UV (DUV) as an alternative to the use of X-ray and e-beam exposure for achieving submicron resolution, and by the late 1970s, IBM had initiated research efforts in this technology. Jain and Willson demonstrated that pulsed excimer lasers using krypton fluoride gas could be used for exposing resist to overcome the low power output of conventional sources. In the 1980s IBM partnered with PerkinElmer, Inc. [now Silicon Valley Group Lithography, Inc. (SVGL)] to develop a step-and-scan exposure system for DUV lithography. This approach, combined with the use of excimer laser sources, is now used by all of the major lithography equipment suppliers for high-resolution, large-field exposures.

Between the mid-1970s and mid-1990s, IBM was also making critical contributions to DUV resists. Early in that

period, IBM successfully applied the concept of acid-catalyzed chemical amplification to resist. This led to the invention of 4-*t*-butoxy-carbonyloxystyrene (TBOC) resist, a very sensitive, high-resolution, etch-resistant material. During the initial implementation of this new type of resist, it was discovered through very clever experiments that low levels of airborne basic compounds in the manufacturing environment could diffuse rapidly into the resist film and cause catastrophic degradation of the imaging. It was also found that carbon filtration of the air in contact with the wafer could alleviate this problem considerably. The technique of using carbon-filtered air is now a common feature for steppers and tracks for environment control. TBOC resist with carbon filtration of the environment was subsequently used in the first high-volume production with DUV lithography to print the recessed oxide isolation level (0.9  $\mu\text{m}$ ) of IBM's 1Mb DRAM in 1986, ten years prior to the mainstream industry adoption of DUV lithography in manufacturing.

In the early 1990s, Shipley introduced the first commercially viable positive-tone DUV resist, APEX, to the market under a licensing arrangement with IBM. Subsequently, workers at the IBM Almaden Laboratory developed an environmentally stable chemically amplified photoresist (ESCAP), which is much less sensitive to airborne contamination and is now the basis for the majority of DUV resists used in the industry.

In parallel with its efforts on optical lithography, IBM was developing electron-beam resist exposure systems. The first e-beam lithography tool, an SEM with computer control, was constructed in the mid-1960s. This laid the foundation for follow-on work, notably at Bell Laboratories, from which today's standard mask-makers (e.g., MEBES by Etec, Inc.) were derived. For increased throughput, a first-of-its-kind (fixed) shaped-beam system, which exposed multiple pixels per shot, was conceived at IBM, and a prototype column was constructed in the late 1960s. The technology spread rapidly throughout the semiconductor industry because it promised to be suitable for manufacturing. IBM implemented several generations of fixed (EL-1) and variable shaped-beam lithography systems (EL-2 . . . EL-3+) in the manufacturing of bipolar device circuits on a large scale between 1975 and 1992. These tools facilitated the efficient production of customized chips for high-performance, industry-leading mainframes.

In the field of mask technology, IBM has made important contributions. EL-4 and EL-4+, the latest in the series of e-beam exposure tools introduced in 1993, have earned the reputation in the industry of being the most advanced and capable mask-makers. IBM was also the first to propose the use of pellicles (thin, transparent polymer covers) to protect masks from damage and defects. In 1982, Levenson suggested the addition of supplemental, nonprinting features to masks that would

cause phase shifting. He showed theoretically and verified experimentally that the addition of 180-degree phase shifters resulted in increased image resolution. Today, phase-shift mask technology is one of the major techniques being used to extend optical lithography.

IBM has also been a leader in developing X-ray lithography. An entire issue of the *IBM Journal of Research and Development* published in March 1993 was dedicated to this subject. The culmination of this effort was the production, at IBM, of a fully functional microprocessor using a compact superconducting storage ring as the X-ray source and a proximity stepper designed with SVGL and the U.S. Defense Advanced Research Projects Agency (DARPA).

The tradition of pioneering research in all aspects of semiconductor lithography continues in IBM, as illustrated by the papers in this issue.

The industry is now moving rapidly toward the use of 193-nm exposure sources. IBM has again been at the forefront in developing innovative materials and processes that address the challenges posed by use of this shorter wavelength. In the early 1990s, scientists from the IBM Almaden Research Laboratory and the MIT Lincoln Laboratory developed a chemically amplified, acrylic-based resist transparent enough to be suitable for 193-nm lithography. While this resist had excellent imaging properties, it lacked sufficient plasma-etching resistance. More recently, the same IBM Almaden scientists collaborated with BFGoodrich Company to exploit a novel transparent, highly etch-resistant polymer for 193-nm resist. The paper in this issue by Ito describes the results of a study of the unusual dissolution characteristics of this polymer, leading to a better understanding of its imaging characteristics.

As with 193-nm lithography, IBM is again working with the MIT Lincoln Laboratory on the development of advanced lithography, this time on 157-nm lithography for sub-100-nm resolution. The critical issues facing the implementation of 157-nm lithography are reviewed in a paper by Bates et al.

One of the approaches for achieving resolutions of 70 nm and below is e-beam lithography. In the early 1990s, researchers at Bell Laboratories initiated an e-beam projection imaging technique designated as SCALPEL (Scattering with Angular Limitation Projection Electron Lithography), which removed a major obstacle—the incompatibility of high-energy electron beams and absorption masks. Later, IBM initiated the PREVAIL (Projection Reduction Exposure with Variable Axis Immersion Lenses) approach, which addressed the excessive electron-optical aberrations of full-chip projection and the development of a viable tool. PREVAIL also combines beam and stage scanning to achieve adequate throughput, a constant concern with

e-beam equipment. In 1995, IBM partnered with Nikon to develop and commercialize this technology. The approach used is described in the paper by Dhaliwal et al.

Two papers in this issue pertain to mask-making technology. Medeiros et al. discuss their recent efforts to develop a dry-etch-resistant e-beam resist that meets the high-sensitivity, high-resolution requirements for future masks. Mask complexity is rapidly increasing as semiconductor companies come to rely on resolution-enhancement techniques such as optical proximity enhancement, phase-shift masks, and subresolution assist features. Liebmann et al. discuss the use of Technology-Computer-Aided Design (TCAD) to address this issue.

Work has continued in IBM on improvements on chemically amplified resists. Two papers in this issue are directed at gaining an understanding of relevant aspects. Hinsberg et al. describe their work on diffusion effects, and Ito reports on detailed studies of the dissolution characteristics of polymers used in such resists.

In addition to these more “mainstream” efforts, IBM continues to seek creative methods of lithographic patterning. Among these are the use of self-assembly systems and the atomic force microscope. Michel describes efforts to utilize an elastomeric stamp to transfer a pattern. While this technique has been used for centuries for printing on paper, his work demonstrates that it can be applied to high-resolution printing.

IBM has a proud tradition of contributing lithography innovations to the semiconductor industry. The work described in this issue has the potential of keeping the company in a leadership position for the foreseeable future.

George J. Hefferon  
Emerging Products Program Manager  
IBM Microelectronics Division  
Hopewell Junction, New York

*Guest Editor*